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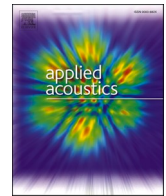
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Effect of irrelevant speech on cognitive performance among normal-hearing and hearing impaired subjects

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ABSTRACT

Open-plan offices are common in the tertiary sector, yet occupants often complain about noise, particularly from co-worker conversations. This issue can differently affect normal hearing people and those with presbycusis. This study therefore examines the impact of mild hearing loss (the onset of presbycusis) on performance in open-plan offices, focusing on the effect of irrelevant speech. An analysis of the decrease in performance on serial recall task as a function of speech-to-noise ratio was carried out with young, normal-hearing subjects under two auditory conditions: with and without a hearing loss simulator, as well as with hearing-impaired elderly subjects. Participants were exposed to five speech-to-noise conditions and silence. Subjective intelligibility was also measured. The results showed a minor, non-significant difference in decrease of performance between normal-hearing and hearing-impaired participants. The hearing loss simulator produced results comparable to those of the older group, validating its efficacy.

1. Introduction

The limited attention given to acoustic comfort for hearing-impaired individuals in the workplace has prompted a study focused on this issue. The demand for more acoustically inclusive workspaces is justified by the growing prevalence of hearing loss among the elderly population, the population ageing, and extended working lives due to pension reforms. Therefore, understanding the acoustic needs of this group is important for contemporary and future society.

Age-related hearing loss, also known as presbycusis, predominantly affects individuals over the age of 50 [1]. The disease is influenced by various factors, including genetics, pre-existing ear conditions, chronic illnesses, noise exposure, medication use, and lifestyle choices [2–4]. The Global Burden of Disease estimates that more than 65 % of people aged over the age of 60 experience some degree of hearing loss [5]. Untreated hearing loss can lead to social withdrawal, early retirement, increased informal caregiving costs, and various physical and mental health issues [6–9].

The aging of the population further exacerbates the problem, especially in some countries such as Japan, Italy, Portugal, Germany and

France where more than 20 % of the population is over 65 years old [10]. This demographic shift poses challenges in terms of economic dependency, productivity, and public finances, potentially necessitating changes in retirement ages and pension systems to address the growing demand for services and support among the elderly [11–13]. In some countries, a significant portion of the senior population is already participating in the labor force e.g., 50.3 % of the Japanese population aged between 65 and 69 [14]. These facts underscore the importance of considering hearing impairments, like presbycusis, in workplace design to ensure better conditions for this population and future generations.

In addition to the challenges related to hearing disorders, this group still has to deal with problems that seem to be nowadays intrinsic to the working environment. Although open-plan office (widespread adopted in workplaces worldwide) are promoted for their benefits — which include cost savings, enhanced communication, and improved teamwork [15–19] —, these layouts are not without their drawbacks. They can lead to decreased productivity, increased health issues, temperature-related problems, and, notably, noise-related challenges [20–26].

Noise is a primary source of distraction [27–29] and has been linked

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to reduced employee satisfaction and productivity in open-plan offices [24,26,30–36], even if the noise level rarely exceeds 60 dB (A-weighted) [37]. The impacts of office noise extend across various domains, including physiological, psychological, cognitive, and social aspects [38–40]. Noise exposure and work-related stress interact in such a way that even low levels of noise can enhance the effects of work-related stress on job satisfaction and well-being [41].

Among all the different sources of noise in open-plan offices, speech is the most annoying one [37], being strongly correlated with the overall perception of disturbing noise [42]. Some aspects of the irrelevant speech, such as its temporal variation, allow it to have direct access to mechanisms that operate memory [43], which can disrupt the execution of other cognitive tasks that use the same resources and mechanisms, such as the Working Memory. This interference phenomenon is known as the Irrelevant Speech Effect — for further details on the theories behind this phenomenon, see [44–46].

The intelligibility of speech, rather than its intensity, plays a crucial role in its distraction potential. Several studies have shown this relationship and models have been proposed to describe the phenomenon, such as Hongisto’s model (2005) and its reformulation [36]. These models introduce the concept of Decrease in Performance (DP), indicating that cognitive performance can decline as the STI exceeds certain levels, with the most significant decrease occurring beyond 0.50.

Hongisto’s model has been proven useful for normal-hearing people, but there does not seem to be an equivalent model for people hearing-impaired people. In their case, background noise affects them more in speech-related tasks [47,48]. However, for non-auditory tasks in a noisy office environment, hearing-impaired individuals might have an advantage as the noise is less noticeable and understandable to them [49].

Therefore, this study aims to verify whether the impact of speech intelligibility in a task involving Working Memory is similar in people with normal hearing and people at the onset of presbycusis, i.e., with mild hearing loss. This loss profile is the one that best fits the context of elderly people, with presbycusis, who may still be actively engaged in the labor market.

2. Experiment 1 – Cognitive Performance

2.1. Methods

2.1.1. Overall design

The first stage of this study involved measuring the Decrease in Performance related to the level of intelligibility of an irrelevant speech, for young individuals with normal hearing and elderly individuals with mild hearing loss (at the onset of presbycusis). This parameter was evaluated through a serial recall test, where participants had to memorize random sets of numbers from 1 to 9 without repetitions. During this task, speech stimuli were presented through headphones, with varying levels of intelligibility based on signal-to-noise ratio (SNR). The choice of intelligibility levels was guided by Hongisto’s model for DP.

Two groups of participants were recruited, a group of normal-hearing and another of hearing-impaired (HI) participants. Moreover, in order to evaluate the effectiveness of a hearing loss simulator in this kind of experiment, the normal-hearing participants performed the experiment twice: with (HIsim) and without the simulator (NH). The simulator is based on an inverse, compressive Gammachirp filterbank to temporarily impair normal-hearing listeners, effectively mimicking hearing loss [50].

The choice of hearing loss profile to be simulated was based on a standard audiogram typical for the onset of presbycusis [51], Fig. 1. This profile also served as a parameter for recruiting older individuals with hearing loss.

Audiological assessments were performed to ensure the participants’ hearing status and provide calibration parameters for the hearing loss

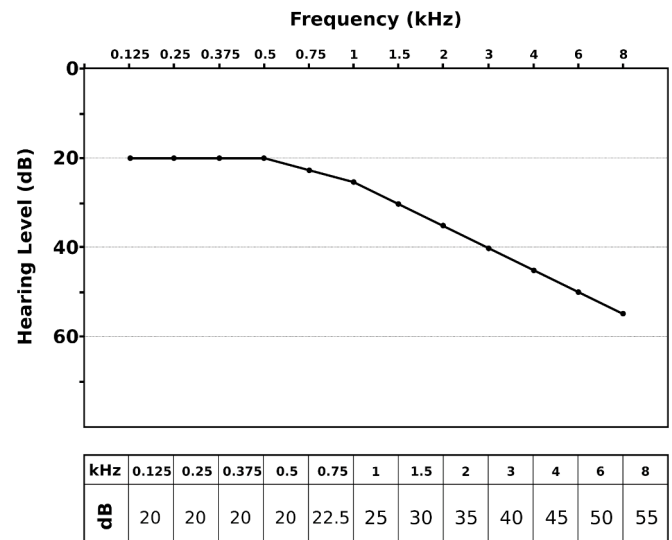


Fig. 1. The standard audiogram that represents the onset of presbycusis.

simulator.

A summary table of groups’ acronyms, Table 1, is provided for reference.

2.1.2. Participants

Thirty-nine (17 females) young normal-hearing native French speakers, mean age of 21 years-old (SD=1; range = 20–23), were recruited among INSA Lyon students, and 17 (8 females) elderly hearing-impaired native French speakers, mean age of 66 years-old (SD=9; range = 50–74), were recruited among patients of a hearing care professional.

The participants were around the same level of education (at least bachelor’s degree, from the French education system). Under these circumstances, it is reasonable to assume that all participants were sampled from the same cognitively high-functioning stratum of the underlying population. All participants were fully informed about the aims of the study, provided written consent and received monetary compensation for their participation.

2.1.2.1. Audiological assessment of hearing. A pure-tone air-conduction audiometry was conducted with every participant in the sound-attenuating booth of the Laboratoire Vibrations Acoustique at INSA Lyon. For the assessment, it was used a Piston PDD-401 Clinical Audiometer, under Eolys Piston XP software, with 3 M PELTOR Optime II headphones, following the procedure recommended by ISO 8253-1:2010.

Normal hearing sensitivity was defined as audiometric thresholds ≤ 20 dB Hearing Level (HL) in both ears at octave frequencies between 0.125 and 4 kHz and ≤ 25 dB HL at 6 and 8 kHz. Regarding the younger group, only those who met the criteria were retained for the study. Audiograms for the normal-hearing and hearing-impaired participants are shown in Fig. 2.

2.1.3. Procedure

The experiment was conducted as follows: a set of numbers from 1 to 9 was randomly displayed on the computer screen, with each number

Table 1
Summary table of acronyms used for refer to each group.

Group	Acronym
Normal-hearing participants	NH
Normal-hearing participants + hearing loss simulator	HIsim
Hearing-impaired participants	HI

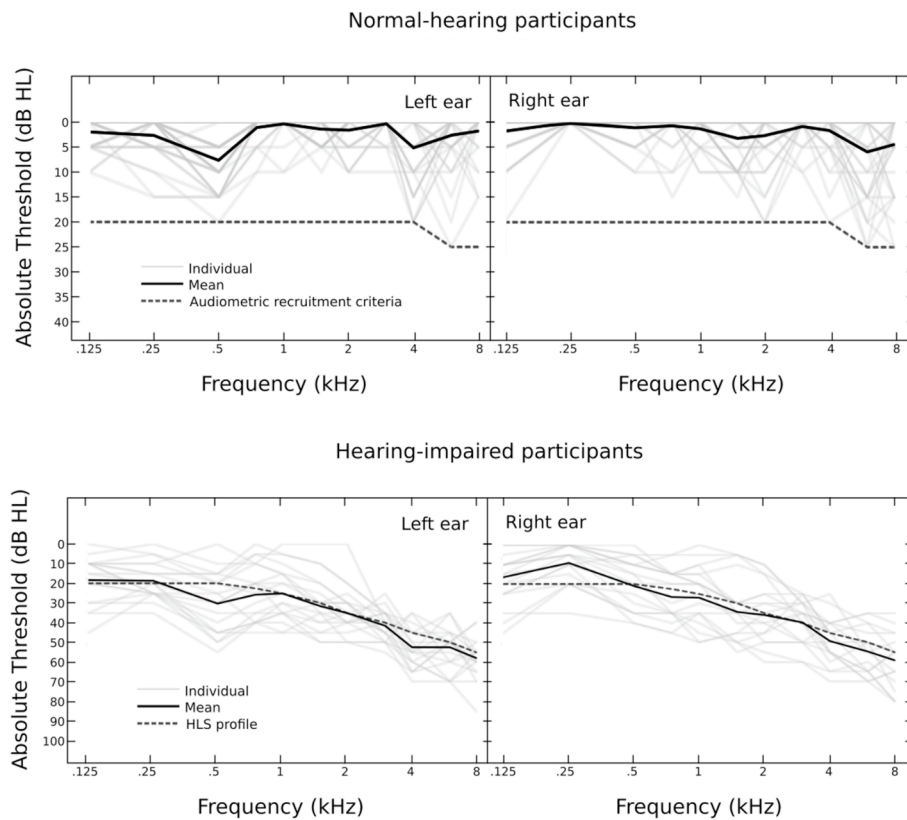


Fig. 2. Results of pure-tone air-conduction audiometry for the left (left panel) and right ears (right panel) of hearing-impaired participants. The light-gray lines represent the individual audiograms. The black line represents the mean audiogram. In the first audiogram, the dashed gray line indicates the audiometric criteria used on the recruitment and, in the second, indicates the standard audiogram choose to represent the hearing loss profile of a person on the onset of presbycusis.

appearing only once, resulting in a total of nine numbers to be memorized, along with their specific order of presentation. Following the presentation of these numbers, the participant was required to use a mouse to select the numbers in the exact order in which they were presented. This process took place in either a silent environment or one of the five distinct noise conditions.

The duration of each number presentation was precisely 1.0 s, and the duration between two following numbers was 0.25 s. Furthermore, there existed a delay of 2.25 s between the presentation of the ninth number and opening of responses. This specific item duration and the seamless transition between items, as suggested by Ellis and Hope [52], was designed to yield a consistent likelihood of accurate responses regardless of presentation rate and serial position when nine items need to be remembered.

Each participant was tasked with completing 20 sets for each value of SNR and silence, resulting in a total of 120 sets. Each noise stimulus was unique and presented only once per session. The order of stimulus presentation was randomized, varying across subjects and between sessions. Notably, stimuli of the same condition were never presented successively within a session, as they were strategically interleaved to prevent immediate repetition of SNR.

Before initiating each session, participants engaged in a pre-session consisting of 12 sets (two sets per condition). This pre-session served the purpose of familiarizing participants with the experiment and ensuring a smooth learning effect; however, its outcomes were not factored into the final results.

Throughout each session, participants had the option to take up to three one-minute breaks, with the timing of these breaks left to the discretion of the individual. The duration of sessions typically ranged from 59 min to 1 h and 2 min, depending on the number of breaks chosen by the participant. The pre-session, designed to prepare the participant, had a duration of 6 min.

Young normal-hearing participants performed the two serial recall sessions on different days and alternately (50 % of them performed the first session with the simulator and 50 % without it), but always the two sessions at the same time of day (morning or afternoon), as a way to maintain the same state of metabolic functions in each session, according to personal circadian rhythm [53,54].

In addition to the serial recall test, participants completed two questionnaires: the NASA Task Load Index (NASA-TLX) — immediately after every serial recall session —, and a hyperacusis questionnaire (HQ) — only once, at the end of the experiment.

The NASA Task Load Index (NASA-TLX) was selected as a tool to evaluate perceived workload following each serial recall session. It is a subjective, multidimensional evaluation tool extensively employed for rating perceived workload when assessing tasks. This questionnaire generates an overall workload score, ranging from 0 to 100, derived from weighted averages across six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration [55].

Hyperacusis, characterized by a distorted perception of loudness, involves the perception of everyday sounds as unbearably loud, even when they are typically considered comfortable by the general population. It is characterized by an exaggerated or inappropriate response to ordinary sounds [56–58]. Khalifa and colleagues [59] introduced a questionnaire to elucidate auditory symptoms and evaluate hyperacusis characteristics. This questionnaire consists of 14 self-rating items categorized into three dimensions: attentional, social, and emotional. A mean score exceeding 28 is indicative of hyperacusis; however, some studies suggest that this threshold may underestimate certain hyperacusis cases [60–62]. Fioretti and colleagues [61] propose that a threshold value of 16 may indicate some level of noise sensitivity.

All the questionnaires were administered in paper-and-pencil format to all participants. The questionnaires were presented in an undisturbed environment outside the sound-attenuating booth at a single table, with

participants provided only with instructions for completion to avoid any potential influence on their responses.

2.1.4. Sound stimuli

Original signals, monologue excerpts from a nonfiction audiobook, were modified to develop stimuli that were aligned with the experiment’s objectives. Moments of silence lasting longer than 0.7 s were removed from the original signals to prevent extended silent periods during the noise conditions of the serial recall task.

Following it, a Gaussian white noise (GWN) was created using MATLAB, and both speech and noise were filtered through a Long-term Average Speech Spectrum (LTASS) filter. The third-octave mean band levels of this speech were sourced from [63] – normal speech, table II.

Speech and GWN were then mixed at different values of Signal-to-Noise Ratio (SNR) to create stimuli (irrelevant speech) with five different levels of intelligibility: -4.5, -1.5, 1.5, 4.5 and 7.5 dB — respectively equivalent to STI 0.35, 0.45, 0.55, 0.65 and 0.75.

The sound pressure level of the stimulus, which was speech mixed with GWN, for the sessions without the hearing loss simulator was set at 56 dB (A-weighted), consistent with the levels observed in open spaces [37,64]. Calibration of the experimental setup was conducted using a binaural dummy head with measuring microphones (Neutrik-Cortex Instruments ‘MANIKIN MK1’) connected to an OROS OR38 system. This calibration ensured that the stimulus levels matched the predetermined values when designing the sounds.

For the sessions simulating hearing loss, the simulation of losses was the last step in the stimuli processing. The final stimuli were individually configured based on the specific audiogram of each young subject and the hearing loss profile selected for this study.

2.1.5. Equipment

Stimuli were played with 24-bit precision through an Echo Gina soundcard hosted in a DELL Optiplex 9020 computer, under the control of a Matlab script. The sampling frequency was 22,050 Hz for stimuli used in the serial recall test. The soundcard output signal was delivered over Sennheiser HD650 headphones to the participants.

The test was performed in a sound-attenuating booth at the Laboratory of Vibration and Acoustics, INSA Lyon.

2.1.6. Determination of the decrease in performance

As per the recommendation of Haapakangas colleagues [36], the DP was calculated as the relative performance difference, i.e., a comparison between performance in silence (P_o) and performance in each noise condition (P_n), as indicated by Eq. (1).

$$DP(\%) = 100 \cdot \frac{P_o - P_n}{P_o} \tag{1}$$

This approach diverges from the method employed by Hongisto [30], which relies on absolute differences. However, considering the modest expectation of achieving 100% performance in this experimental context and the limited likelihood of encountering ceiling effects, the relative comparison method proves to be the most suitable choice for this study [36].

2.1.7. Statistical analyses

Bayesian statistical methods were employed for data analysis in this study. Group and condition disparities were assessed through Bayesian repeated-measures analysis of variance (Bayesian RM ANOVA). The higher-order interactions were excluded from the analysis of effects. In certain instances, a Bayesian post hoc analysis, which followed the Westfall’s approach for multiple comparisons, was conducted to ensure the reliability of the prior analysis.

In the comparisons between NH and HIsim, the samples were treated as paired data, with the group considered a within-subject factor — since the two groups are composed of the same subjects. Conversely, when comparing these two groups with the HI group, the samples were

treated as independent, and the group was regarded as a between-subject factor. The level of intelligibility of the speech (SNR) was always considered as within-subject factors.

Although the Bayes factor has a clear and continuous scale, it can be helpful to summarize it using discrete categories of evidential strength, Table 2. These labels aid scientific communication but should be regarded only as an approximate description of different standards of evidence [65].

2.2. Results and discussion

The sets and responses were categorized based on SNR values, and a comparative analysis was conducted between the subjects’ responses and the provided numerical data to ascertain performance within each condition. Table 3 displays the mean performance of each group.

The difference in performance between young and elderly individuals was also documented in other studies [67]. Although this difference seems to be significant, studies have shown that young and old people are equally affected by the Irrelevant Speech Effect [68] and that this difference in performance does not impact the DP.

Following it, the decrease in performance under noisy conditions was quantified in relation to the quiet condition. Table 4 and Fig. 3 show the mean DP for each group.

The three groups exhibit similar outcomes, both in terms of values and response patterns, with the DP being directly proportional to the SNR, in accordance with previous research.

Upon examining the Fig. 3, several observations can be made: 1) SNR appears to exert a significant influence on DP in the NH but likely plays a less important role in the HIsim and HI; 2) HIsim and HI exhibit similarities, although HI shows wide variability.

There is indeed moderate evidence of an SNR effect on DP in the NH ($BF_{10} = 6.441$), but a post hoc analysis reveals that the only significant DP differences in the NH condition are between SNR 7.5 dB and SNRs 1.5 ($BF_{10} = 21.650$), -1.5 ($BF_{10} = 24.846$), and -4.5 dB ($BF_{10} = 9.424$). Analysis also shows anecdotal evidences of an effect for HIsim and HI ($BF_{10} = 1.836$ and $BF_{10} = 0.288$, respectively).

In the model comparison of NH vs. HIsim, there is anecdotal evidence ($BF_{10} = 0.625$, $BF_{incl} = 0.464$) of an effect from the hearing-condition, but moderate evidence of an interaction between this predictor and SNR ($BF_{10} = 3.647$). However, an analysis of effects provides some support for excluding the interaction effect from the model ($BF_{incl} = 0.906$). The model comparison of NH vs. HI also suggests anecdotal evidence of an effect from the hearing-condition ($BF_{10} = 0.605$, $BF_{incl} = 0.608$) and an interaction with SNR ($BF_{10} = 0.475$, $BF_{incl} = 0.106$).

The HI vs. HIsim model indicates moderate evidence ($BF_{10} = 0.299$, $BF_{incl} = 0.305$) of no effect of the hearing-condition, i.e., evidences of similarity between these two groups, and very strong evidence ($BF_{10} = 0.099$, $BF_{incl} = 0.058$) of no interaction between this predictor and SNR. This suggests that the simulator can yield results similar to

Table 2
Evidence categories for the Bayes factor BF_{10} [65,66].

Bayes factor BF_{10}	Interpretation
> 100	Extreme evidence for M_1
30 – 100	Very strong evidence for M_1
10 – 30	Strong evidence for M_1
3 – 10	Moderate evidence for M_1
1 – 3	Anecdotal evidence for M_1
1	No evidence
1/3 – 1	Anecdotal evidence for M_0
1/10 – 1/3	Moderate evidence for M_0
1/30 – 1/10	Strong evidence for M_0
1/100 – 1/30	Very strong evidence for M_0
< 1/100	Extreme evidence for M_0

Note: M_0 represents the null hypothesis.

Table 3
Mean values of groups' performance in the serial recall test.

SNR (dB)	Performance (%) ¹					silence
	-4.5	-1.5	1.5	4.5	7.5	
NH	80.1 (12.2)	79.8 (13.8)	79.3 (12.8)	78.7 (13.7)	76.1 (14.7)	85.3 (11.7)
HIsim	83.1 (10.6)	82.2 (11.4)	80.8 (12.9)	79.6 (13.3)	81.3 (12.7)	86.2 (10.0)
HI	68.1 (12.1)	64.4 (15.8)	63.8 (17.8)	62.5 (17.6)	63.1 (19.5)	68.8 (15.6)

Notes: ¹ Mean (SD).

Table 4
Mean values of decrease in performance (DP) as a function of SNR.

SNR (dB)	DP (%) ¹				
	-4.5	-1.5	1.5	4.5	7.5
NH	5.94 (8.09)	6.42 (9.76)	6.93 (8.86)	7.53 (11.78)	11.13 (9.58)
HIsim	3.40 (6.72)	4.55 (7.65)	6.36 (9.23)	7.91 (8.78)	5.79 (8.85)
HI	-0.46 (14.56)	3.55 (10.92)	5.03 (13.20)	7.09 (10.53)	6.84 (12.93)

Notes: ¹ Mean (SD).

those of individuals with hearing impairment.

Although the NH condition exhibits higher DP values than the others, there is no consistent evidence of a distinction between these two conditions and the NH condition. This implies that, from a statistical perspective, there is no apparent difference in the impact of irrelevant speech on individuals with normal hearing and those with age-related mild hearing loss, as another study has shown [69].

Having examined the impact of objective parameters on the DP, which encompasses factors like intelligibility and hearing-condition, it becomes now important to evaluate the possible influence of subjective parameters, such as noise sensitivity (hyperacusis) and perceived workload.

In line with what had been proposed by Fioretti colleagues [61], participants scoring above 16 on Khalifa's Hyperacusis Questionnaire were classed as having some degree of noise sensitivity. Table 5 presents both the average scores of the participants and the distribution of noise sensitivity in this study.

Participants with normal hearing and those with hearing impairments exhibit similar averages and only a slight disparity in the

proportion of individuals sensitive to noise. Notably, when comparing genders, females seems to have a higher prevalence of noise sensitivity compared to males, aligning with existing literature [70].

Both model comparisons yield anecdotal evidence of an effect of noise sensitivity ($BF_{10} = 0.715$, for normal-hearing participants, and $BF_{10} = 0.475$, for hearing-impaired participants), thus suggesting that DP may not have a connection with this factor. This also implies that the available data may not provide sufficient support for establishing a discernible relationship between noise sensitivity and the Irrelevant Speech Effect.

An investigation was also conducted to ascertain whether there is a potential relationship between participants' DP and their perceived workload. Please note that the latter represents the overall workload value for each hearing condition, since it was not possible to assess this parameter for each noise condition, as they were mixed and presented randomly in each session.

The average perceived workloads among the groups display remarkable similarity (NH: mean = 70.7 and SD=11.8; HIsim: mean = 68.2 and SD=11.5; HI: mean = 65.5 and SD=13.4). In general, the NH exhibits the highest value, followed by the HIsim and HI, aligning with expectations. Mental demand stands out as the most prominent dimension on the workload scale, closely followed by effort.

In both model comparisons, there is anecdotal evidence ($BF_{10} = 1.422$, for normal-hearing participants, and $BF_{10} = 0.404$, for hearing-impaired participants) either indicating a relationship or its absence between perceived workload and DP under noisy conditions. Regarding normal-hearing participants, there is also anecdotal evidence suggesting no influence of hearing condition and no interaction between this predictor and perceived workload ($BF_{10} = 0.913$). Consequently, we can confirm that the difference in perceived workload between the NH and HIsim is not substantial, even though their DP in noisy environments shows slight distinctions.

Table 5
Assessment of participants' noise sensitivity.

Participants	Mean (SD)	Tested positive for noise sensitivity (%)
Normal hearing	15.0 (4.9)	35.9
Hearing impaired	15.2 (6.7)	47.1
Males	14.6 (4.6)	29.0
Females	15.7 (6.4)	52.0

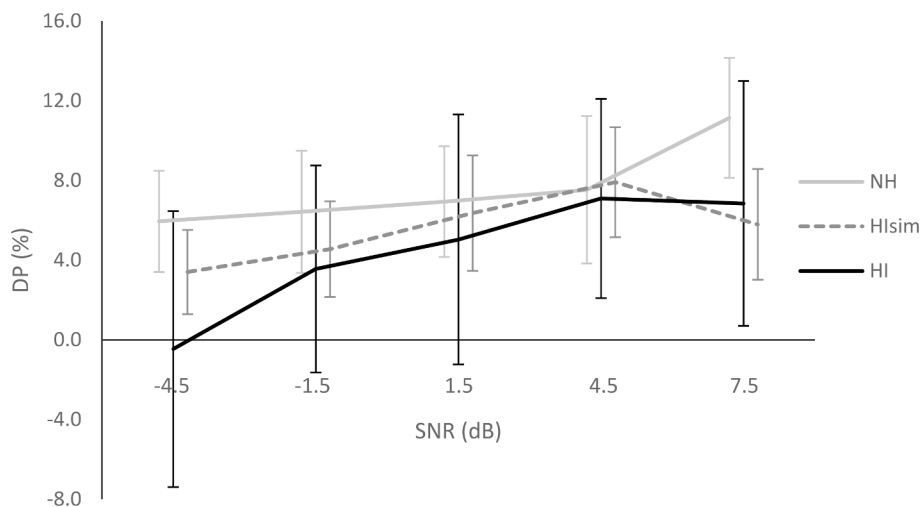


Fig. 3. Comparison of the DP of the groups as a function of SNR. Mean values are presented with their corresponding confidence intervals (95%).

3. Experiment 2: Speech Intelligibility

3.1. Methods

3.1.1. Overall design

After the serial recall test conducted with the group of young normal-hearing subjects (with and without a hearing loss simulator), questions were raised around the difference in DP between the conditions with and without simulator. Those differences were inferred to be intrinsically related to the level of subjective intelligibility of the stimuli, which differentiates it from the SNR. In fact, two stimuli with the same SNR can have different levels of subjective intelligibility for people with and without hearing loss.

Thus, a speech intelligibility test was conducted to assess the subjective level of intelligibility of signals with the same SNR of those of the first stage. In this task, the participants listened to phonetically balanced sentences in French — Combesure's [71] and Fournier's [72] lists — and were asked to repeat what they understood. The same three classes of subjects performed this stage, i.e., younger normal-hearing subjects (with and without a hearing loss simulator) and older hearing-impaired subjects.

3.1.2. Participants

The need to conduct subjective speech assessments arose after analyzing the results of the serial recall test of the younger normal-hearing listeners, but before conducting the test with the older hearing-impaired listeners. In this way, both the serial recall test and the speech intelligibility test could be conducted with all the same participants from the latter group. However, it was necessary to recruit younger normal-hearing participants, to perform both conditions (with and without hearing loss simulator).

Therefore, a group of 24 subjects (8 females), mean age of 21 years-old ($SD = 1$; range = 19–24), was recruited among INSA Lyon students. The participants were around the same level of education as the previous participants, and were also fully informed about the aims of the study, provided written consent and received monetary compensation for their participation.

3.1.2.1. Audiological assessment of hearing. Audiological assessments were performed to ensure the participants' hearing status and provide calibration parameters for the hearing loss simulator, as followed in the previous stage.

Also, the same materials were used and the same method and criteria were followed as in the previous stage. Audiograms for the second group of normal-hearing participants are shown in Fig. 4.

3.1.3. Procedure

Participants were instructed to verbally reproduce the sentences they heard, aiming to replicate them word for word. In cases where the subject did not comprehend the entire sentence, they were allowed to repeat the words they did understand. No specific time constraint was imposed on these repetitions. Following each repetition, the count of correctly repeated words was documented.

In contrast to the serial recall test, there was no preliminary familiarization session. Each stimulus, in the form of sentences, was presented only once. Each participant listened to 15 sentences per condition, totaling 75 sentences. The sequence of sentence presentations was randomized and varied among subjects. Within a single session, a sentence from one condition was never immediately succeeded by another sentence from the same condition. Consequently, the conditions were intermingled to prevent immediate repetition.

Throughout both stages of the experiment, participants were provided with limited information and instructions regarding the test to avoid influencing their performance. The participants were closely supervised during the experiment and were not allowed to exit the sound-

attenuating booth, even during scheduled breaks.

3.1.4. Sentences setup

Both the stimuli, for the serial recall test, and sentences, for speech intelligibility assessment, were processed in the same way, except for the adjustment in the duration of moments of silence in the audiobook excerpts, which was not applied to the sentences. Also, in this phase, the simulator was not configured individually taking into account the audiogram of each participant, as was done in the previous experiment. Instead, it was configured with an audiogram at 0 dBHL at all frequencies and the hearing loss profile used in the previous experiment.

3.1.5. Equipment

The same equipment was used as in the previous stage, but the sampling frequency was 44,000 Hz for the stimuli used in speech intelligibility assessment.

3.1.6. Determination of the speech intelligibility

Speech intelligibility for sentences was determined based on the criterion that a sentence was considered intelligible when the subject could reproduce it entirely and accurately, word for word. Consequently, the calculation of speech intelligibility for sentences was carried out for each SNR, as outlined in Eq. (2).

$$\text{Speech Intelligibility (\%)} = 100 \cdot \frac{\sum \text{Right sentences}}{\sum \text{Sentences}} \quad (2)$$

3.2. Results and discussion

Table 6 and Fig. 4 present the mean results for each hearing condition.

As expected, subjective intelligibility increases with the SNR. The HIsim and HI groups, in general, demonstrate a lower intelligibility rate compared to the NH group. Furthermore, these two conditions display a very similar rate, albeit with varying levels of variability.

Upon examining the results, three key assumptions can be derived: 1) The NH reaches a ceiling of intelligibility at SNR 1.5 dB; 2) There is no significant difference between the HI and HIsim conditions, but a substantial discrepancy between both and the NH condition; and 3) The SNR 7.5 dB in the HI and HIsim conditions yields a similar level of speech intelligibility as the SNR −4.5 dB in the NH condition.

In the NH, all SNR values differ from each other, except for the three highest values (1.5, 4.5, 7.5), for which there is anecdotal evidence ($0.221 < BF_{10} < 2.887$) of a difference or the absence thereof between them. This analysis corroborates that NH participants achieved the ceiling of speech intelligibility at SNR 1.5, which may be equivalent to STI 0.55.

The model comparisons reveal strong evidence (all $BF_{10}/BF_{incl} > 100.000$) of a disparity between the NH and the other two conditions, along with an interaction between hearing condition and SNR (all $BF_{10}/BF_{incl} > 100.000$). Also, there is moderate evidence indicating no substantial difference between HIsim and HI groups ($BF_{10} = 0.239$), and an analysis of effects suggests it is preferable to exclude hearing-condition ($BF_{incl} = 0.530$) and the interaction between hearing condition and SNR ($BF_{incl} = 0.062$) from this model comparison.

For the last assumption, Bayesian t-tests (paired samples for the NH vs. HIsim comparison and independent samples for the NH vs. HI comparison) show anecdotal/moderate evidences of a difference in intelligibility between SNR −4.5 dB from NH and SNRs 4.5 and 7.5 dB from HIsim and HI ($0.220 < BF_{10} < 0.395$).

4. Further consideration

4.1. Decrease in performance vs speech intelligibility

Given the apparent connection between the differences in DP and

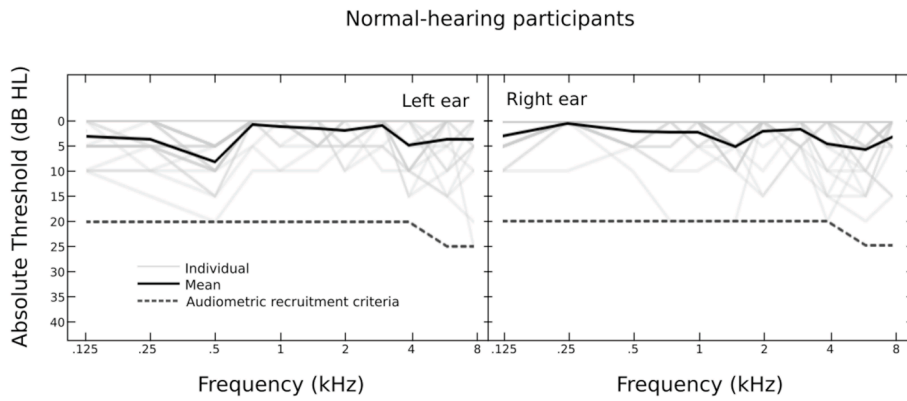


Fig. 4. Results of pure-tone air-conduction audiometry for the left (left panel) and right ears (right panel) of young normal-hearing participants. The light-gray lines represent the individual audiograms. The black line represents the mean audiogram. The dashed gray line indicates the audiometric criteria used on the recruitment.

Table 6
Mean values of speech intelligibility for sentences per SNR.

SNR (dB)	Speech Intelligibility (%) ¹				
	-4.5	-1.5	1.5	4.5	7.5
NH	63.33 (20.99)	86.67 (14.45)	93.61 (10.12)	97.50 (4.31)	97.78 (4.68)
Hlsim	6.10 (7.33)	31.67 (15.26)	53.61 (15.41)	62.50 (14.01)	68.33 (16.36)
HI	6.67 (9.67)	29.67 (26.62)	47.33 (28.28)	57.00 (30.63)	68.33 (26.03)

Notes: ¹ Mean (SD).

speech intelligibility among groups, it is interesting to further examine this relationship. Fig. 5 illustrates a clear and noteworthy relationship between the level of intelligibility of irrelevant speech and its adverse influence on cognitive task performance.

Unfortunately, the results fail to account for the disparity in the decrease in performance between the final three noise conditions within the NH group, SNRs 1.5, 4.5 and 7.5 dB, despite the equivalent speech intelligibility levels among them.

4.2. Effortless Intelligibility

It is important to consider that during the speech intelligibility assessment, participants exclusively focus on listening to and repeating sentences (relevant speech), allowing them to dedicate all their cognitive resources to a single task. In contrast, during the serial recall task, participants must split their attention between memorizing series of numbers and listening to irrelevant speech, even if they attempt to ignore it. In this scenario, most of their cognitive resources are directed toward number retention, leaving only a limited portion available for processing speech, which is also influenced by its level of intelligibility. Consequently, it is reasonable to assert that the retention of speech during a cognitive task is not the same as during a conversation, even if both have the same level of intelligibility.

Ideally, the most appropriate approach to assess the impact of irrelevant speech on the performance of a concurrent cognitive task would be to consider the amount of speech processed and retained at that moment. However, this parameter is not easily accessible and is difficult to measure.

Nevertheless, the relationship between speech intelligibility and listening difficulty — i.e., the effort required to understand speech under adverse conditions — could potentially serve as a valuable estimation for this parameter. Sato and colleagues [73,74] proposed a listening difficulty model for normal-hearing listeners and another model for elderly listeners with mild hearing loss [75], whose subjects had a

similar hearing loss profile and age range to those in the current study. In the latter, the authors found that, for the same level of intelligibility, elderly subjects (normal or hearing-impaired) experienced less listening difficulty than younger subjects.

The listening difficulty models — [73,74] for NH and [75] for HI and Hlsim — and the speech intelligibility model were combined, resulting in a new parameter named effortless intelligibility (Eq. (3)).

$$Effortless\ Intelligibility\ (\%) = \frac{Speech\ Intelligibility}{e^{\frac{Listening\ Difficulty}{100}}} \quad (3)$$

The DP values for each group were related to their respective effortless intelligibility values, Fig. 6.

The decrease in performance is strongly related to effortless intelligibility, supporting the idea that a parameter considering the amount of information involuntarily retained is more likely to explain the Irrelevant Speech Effect than speech intelligibility alone (whether objective or subjective).

However, more evidence and data are needed to validate the model. Nonetheless, these considerations are both necessary and important for raising thought-provoking questions that may stimulate further research in this domain (See Fig. 7).

5. Conclusions

The Irrelevant Speech Effect was evident across all hearing conditions assessed. The young normal-hearing group without the hearing loss simulator showed a relatively higher rate of decrease in

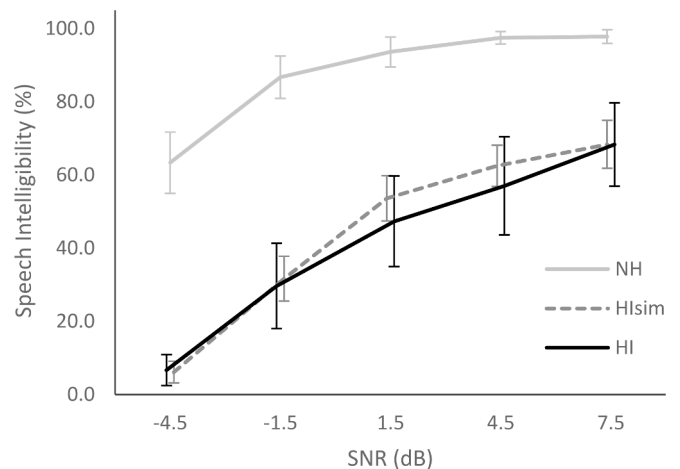


Fig. 5. Comparison of the level of speech intelligibility of the groups. Mean values are presented with their corresponding confidence intervals (95%).

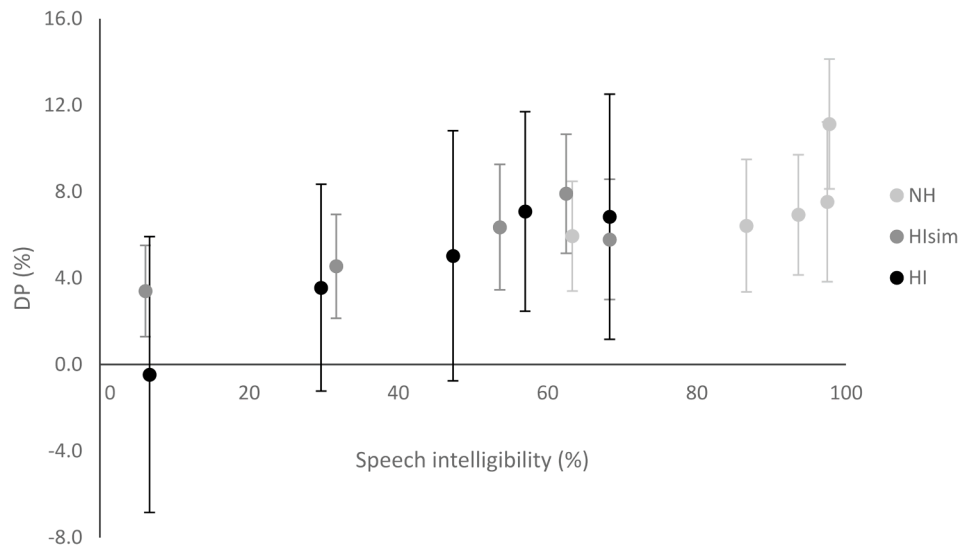


Fig. 6. Comparison of the DP of the groups related to their speech intelligibility. Mean values are presented with their corresponding confidence intervals (95 %).

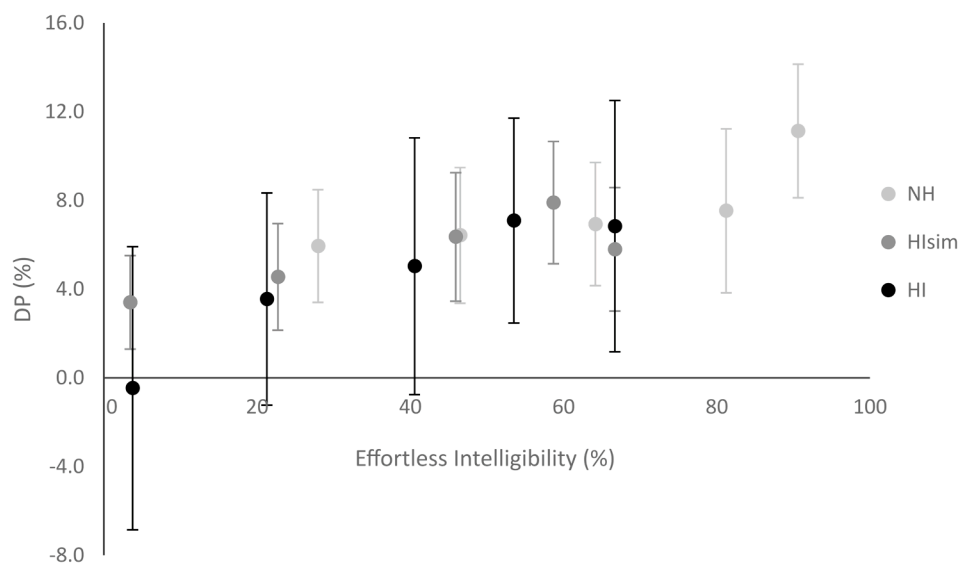


Fig. 7. Comparison of the DP of the groups related to their effortless intelligibility. Mean values are presented with their corresponding confidence intervals (95 %).

performance compared to the others, though this difference was not statistically significant. Thus, no specific impact of mild hearing loss on the relationship between intelligibility and decrease in performance was found. Additionally, subjective parameters such as noise sensitivity and perceived workload did not correlate with participants' decrease in performance.

Regarding speech intelligibility, the young normal-hearing group with the hearing loss simulator and the elderly hearing-impaired group were statistically indistinguishable from each other but differed from the young normal-hearing group without the simulator, which had the highest overall intelligibility. These results suggest that the variation in decrease in performance among the three hearing conditions can be attributed to differences in the subjective intelligibility of the irrelevant speech. Furthermore, these results suggest that the hearing loss simulator can be used in studies about the detrimental effects of speech on performance, at least when focusing on mild hearing losses.

Finally, it is proposed to improve the model that relates speech intelligibility to decrease in performance decrease by incorporating the Listening Difficulty model. This can enhance the correlation at the

highest levels of speech intelligibility.

CRediT authorship contribution statement

Nicolas F. Poncetti: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Etienne Parizet:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Edith Galy:** Writing – review & editing, Validation. **Patrick Chevret:** Writing – review & editing, Validation. **Laurent Brocolini:** Writing – review & editing, Validation. **Vassia Peytcheva:** Writing – review & editing, Validation.

Declaration of competing interest

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